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PERFORMANCE REPORT

NEURAL NETWORKS FOR

REAL-TIME SENSORY DATA PROCESSING

AND SENSORIMOTOR CONTROL

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## 1. Experimental Work

One of the critical problems that we faced in modeling the neural control of escape turns in the cockroach was a quantitative analysis of the leg movements that generate the turn. Because the turn is very rapid, often spanning no more than 20 msec, conventional motion analysis techniques could not be employed. For that reason, we acquired an NAC high speed video and computer motion analysis system. With these tools, we have now attained a very good description of the movements that occur at each joint of each leg during turns in response to wind from four different angles relative to the animal's body. Figure 1 is a typical stick figure generated by the computer system showing four successive frames at 5 msec intervals. The pairs of legs shown are, from front to back, legs in the prothoracic (T1), mesothoracic (T2), and metathoracic segments. In all legs the coxa, femur, and tibia segments are shown. These segments make two critical joint angles: the coxal-femur (C-F) joint and the femoro-tibial (F-T) joint.

Our data indicate that the legs of each segment play very different roles during the turn. The mesothoracic legs appear to provide the primary direction for the turn, whereas the metathoracic legs provide more power than direction. Figure 1 shows how this is accomplished. The movement shown in this figure is a turn in response to a wind stimulus from 60° left (indicated by the arrow). The mesothoracic legs in this turn both moved posteriorly due to increases in the C-F joint angles. At the same time, the angle made by the F-T joint ipsilateral to the wind source increased, while the angle of the contralateral F-T joint decreased. As a result, both legs move posteriorly and towards the wind source. In a free-ranging animal this would generate a force that would turn the animal away from the wind source.

In contrast, the metathoracic legs both thrust backwards, providing power to overcome inertia but no left-right directionality. Winds from the rear caused the C-F joints of both metathoracic legs to increase in angle. However, unlike the mesothoracic legs, the changes in the F-T joints of the metathoracic legs are approximately equal to changes at the C-F joint of the same leg. As a result, the force produced by these legs is largely parallel to the long axis of the animal's body. As the wind stimulus is changed to more anterior positions, the contralateral C-F joint will often reverse direction, pushing forward on the side away from the wind. In a free-ranging animal, this would result in a larger turn in response to winds from the front.

With these data, we can now translate the escape turn into individual movements of specific joints. We are presently attempting to relate these movements to activity in specific muscles that control movement around the F-T joints. Once we have accomplished this, we will be able to identify turn activity in restrained animals that are set up for detailed electrophysiological recordings.

STATEMENT "A" per Donald Woodward  
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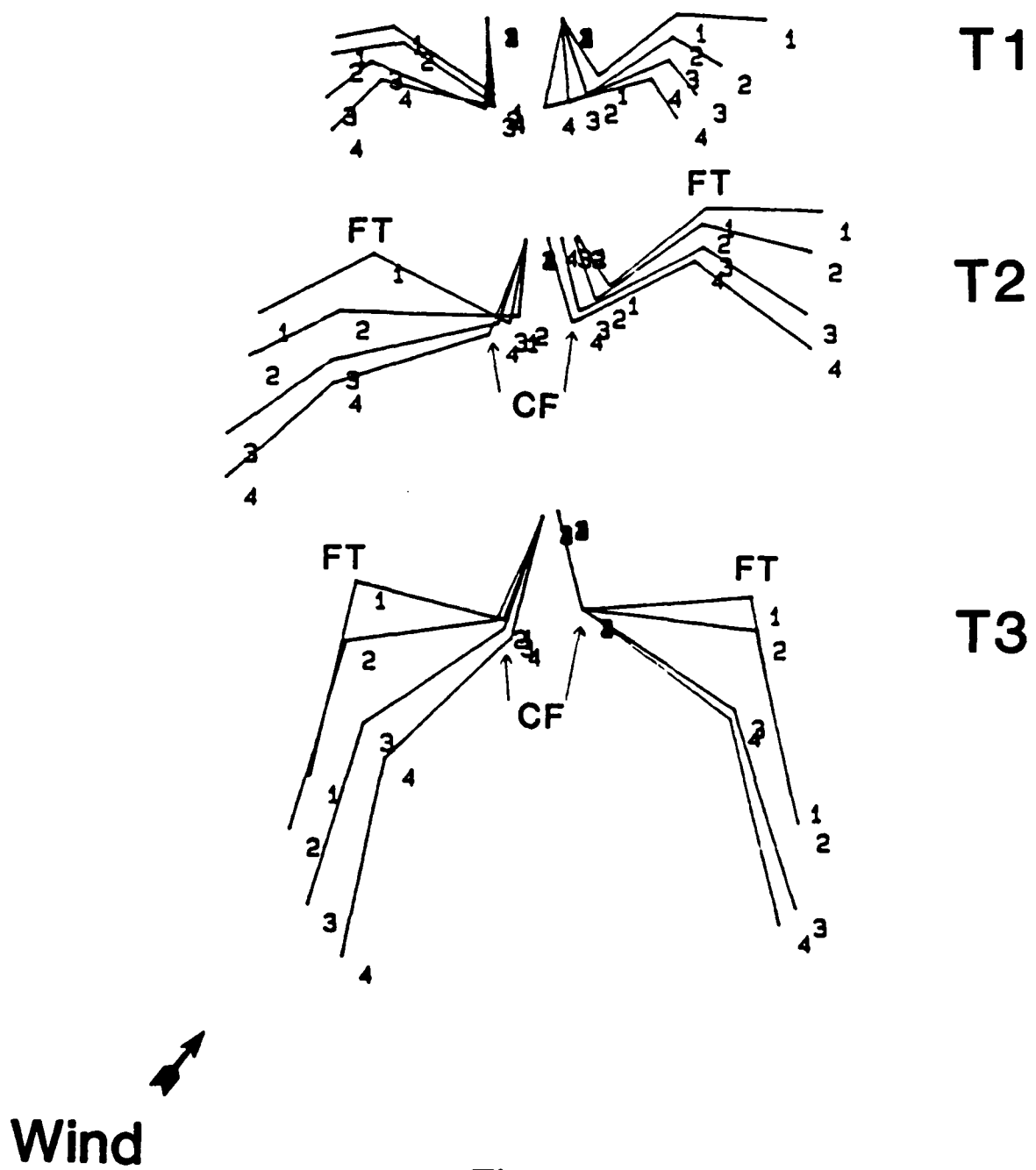


Figure 1

## 2. Modeling and Simulation

We originally planned to make use of the GENESIS neural simulation system developed by Jim Bower at Caltech as the core of our model. However, after further evaluation, we decided that GENESIS was not sufficiently robust or well-documented. We have therefore designed and implemented our own simulation system in C and X on a DEC 3100. This system features an interactive command-line interface and a variety of graphical display tools (Figure 2).

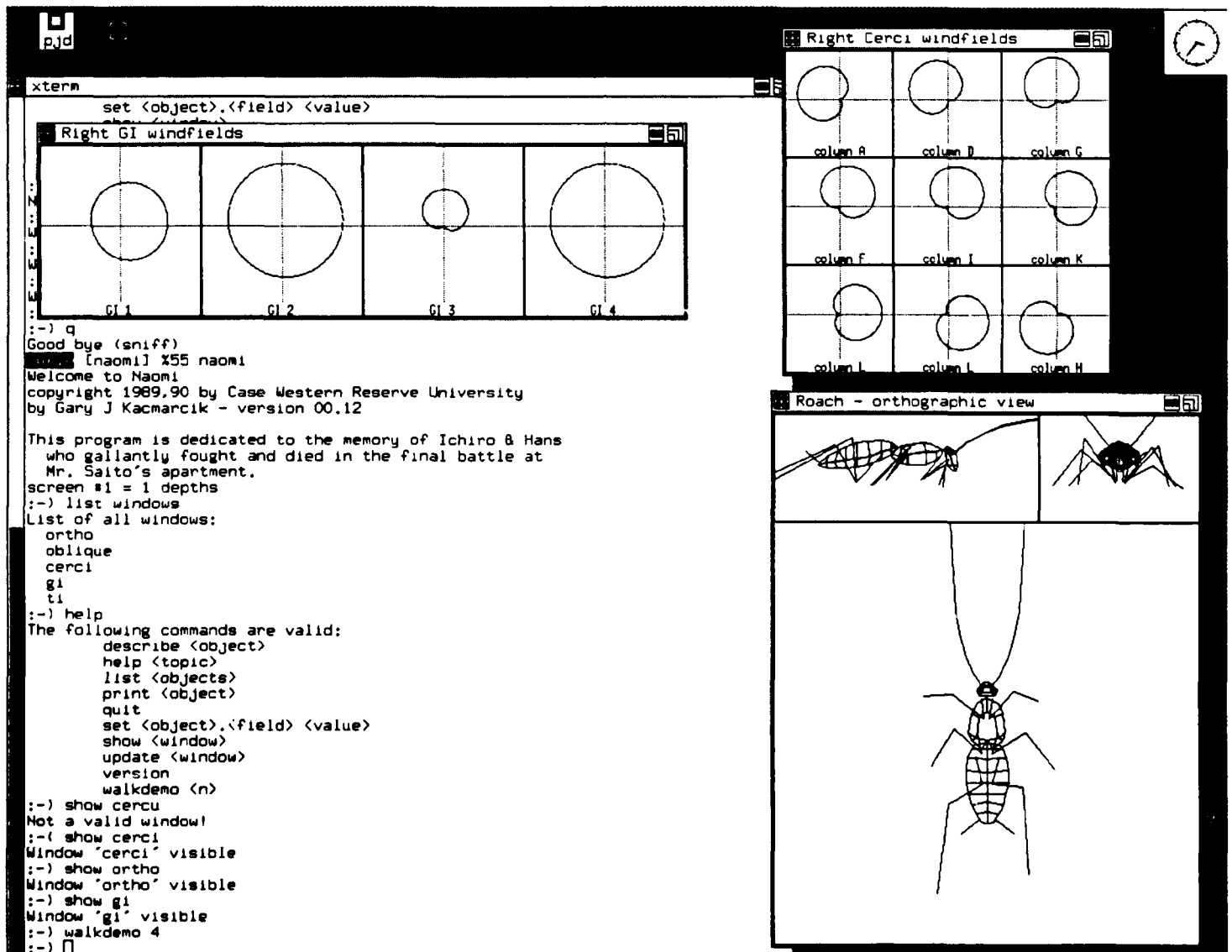
A three-dimensional kinematic model of the insect's body has been developed (Figure 2). Of primary interest for the escape response are the insect's cerci and legs. The directionally-tuned wind responses of the nine most prominent columns of hairs on each cercus were represented as cardioids. The segment and joint characteristics of the legs were derived from experimental measurements. Currently, each leg possesses only two degrees of freedom, representing the C-F and F-T joints described above, because preliminary data suggested that these were primarily responsible for the turn. However, more recent motion analysis with the high speed video camera has suggested that it will be necessary to add a third degree of freedom to the middle legs in order to fully account for their role.

While a great deal is currently known about the overall response properties of the individual neurons and their architecture of connectivity, little detailed biophysical information is available. For this reason, our initial models of the neuronal circuitry have employed simplified neural network models and learning techniques in order to explore the distributed processing employed in this circuit. Specifically, we have utilized the back-propagation learning algorithm constrained by known properties of the circuitry (e.g. the existence, sign, and relative magnitude of connections). It is important to note that we are employing back-propagation solely as a means for finding the appropriate connection strengths given the known structural constraints on the circuit, and no claim is being made about its biological validity.

Using this approach, a number of preliminary results have been obtained. First, we examined the ability of the known circuitry to account for the observed ventral giant interneuron (vGI) windfields by training two-layer networks constrained by the known properties of the cercal-hair-to-vGI connections. These networks were able to accurately reproduce the observed windfields. Furthermore, the accuracy of the vGI windfields was much better when the cercal hair responses were modeled as cardioids than when the cosine functions that have been suggested by previous investigators were employed.

In a second series of experiments, we examined the ability of the known circuitry to account for the directionality of the turn by training a four layer network to generate a turn of the appropriate magnitude to the left or right depending on the wind direction. The network had 18 input units (cercal hairs), 8 units in the first hidden layer (vGIs), 12 units in the second hidden layer (representative thoracic interneurons), and two output units which encoded the mag-

Figure 2



nitude of the turn. All known constraints on the cercal-hair-to-vGI and vGI-to-TI connections were enforced. After training, the network was able to produce turns of the appropriate magnitude and direction. Interestingly, units in the vGI layer developed omnidirectional, front/back biased, and left/right biased windfields, as are observed in the actual vGIs. Our next step will be to extend these networks to control the leg movements of the model insect.

### 3. Robotics

A hexapod robot has been designed. The first two segments of the frame, including one complete and one incomplete leg assembly, is shown in Figure 3. The frame will be constructed from 1/8 inch Lexan and will have an overall dimension of approximately 15" by 9". Leg assemblies will be placed in alternate gaps in the frame. Each leg has three degrees of freedom: raising or lowering (using a chain and pinion); swinging forward or back parallel to the body (using a half-gear mounted on the leg); swinging away from the body (using a full gear attached to the entire leg assembly). The latter degree of freedom will be frozen in our initial experiments with controlling the robot.

The legs will be driven by 2 watt motors ordered from Maxon Precision Motors. With gearbox, these motors have an overall length of 47.7 mm. Both swing motors use a gearbox with a reduction of 35.6:1, and an additional 4:1 reduction is provided by the half-gear. The lifting motors have a gearbox reduction of 12.9:1. These motors have low inertia (resulting in high acceleration characteristics), low electromagnetic interference, low electrical noise, and small inductance. They have high efficiencies, are able to withstand overloads, and have a very long life. Finally, their compact design makes them easier to fit into the leg assemblies.

Two types of potentiometers have been ordered from Spectrol. A single turn potentiometer will be used to encode the position of the swing motors, while a ten turn potentiometer will be used for the lift motors. The potentiometers are 1/2" in diameter and .305" long for the single turn and 1" long for the ten turn.

In addition to designing the robot hardware, we have also ported the locomotion controller (originally implemented in Lisp on a TI Explorer Lisp Machine as part of the Artificial Insect Project) to C on an PC. This will allow the simulated controller to directly drive the robot while we are debugging it. Clearly, the next step is the actual construction of the robot itself.

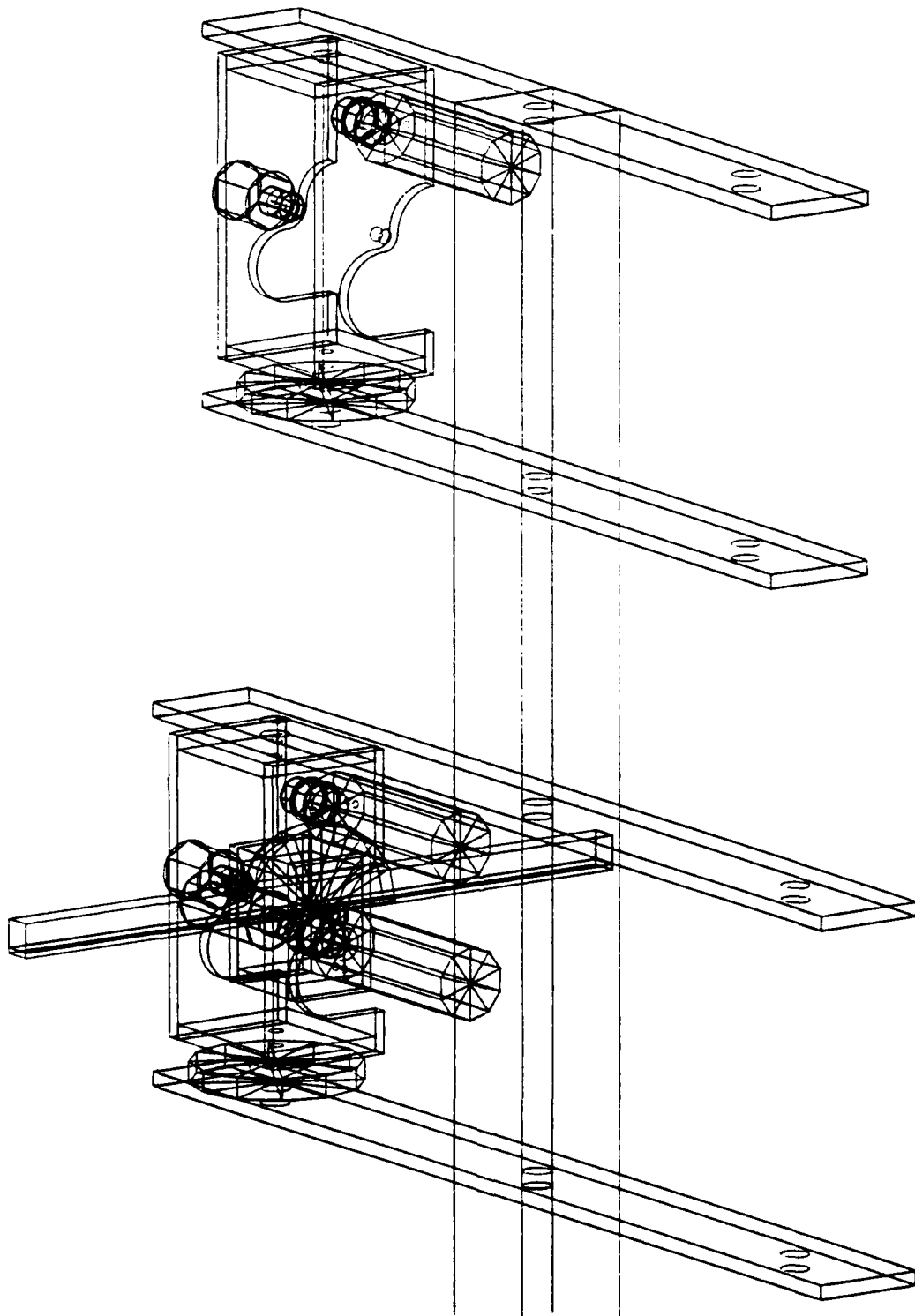


Figure 3